

OSCILLATORY MOTION BASED
MEASUREMENT METHOD AND
SENSOR FOR MEASURING WALL
SHEAR STRESS DUE TO FLUID
FLOW

Patent Application
of

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OSCILLATORY MOTION BASED MEASUREMENT METHOD AND SENSOR FOR MEASURING WALL SHEAR STRESS DUE TO FLUID FLOW

1 The present application is a continuation and claims priority of
2 PCT/US2004/015904, filed May 20, 2004, and provisional patent application Serial No.
3 60/472,347, filed on May 21, 2003.

4 5 BACKGROUND OF THE INVENTION

6 1. Field of the Invention

7 This invention relates generally to a shear stress sensor and, more particularly, the
8 invention relates to a dynamic resonant wall shear stress sensor having high bandwidth,
9 high spatial resolution, and high sensitivity capable of fluctuating wall shear stress
10 measurements in all kinds of fluid flows on all kinds of surfaces.

11 12 2. Description of the Prior Art

13 The measurement of unsteady wall shear stress (also called surface shear stress or
14 skin friction) remains one of the great unsolved problems in experimental fluid
15 mechanics. This is in spite of the long history of development of wall shear stress
16 measurement techniques by some of the greatest fluid mechanics and instrumentation
17 experts. Shear stress sensors are required for military, biomedical, and industrial
18 applications as well as for basic understanding of wall-bounded flows. For example, it
19 has been shown computationally that skin-friction drag can be substantially reduced using
20 closed loop control of an actuator with feedback provided by a shear stress sensor capable
21 of fluctuating shear stress measurements. However, no rigorously calibrated wall shear
22 stress sensors with such capabilities exist today.

23 Although the measurement of wall shear stress has been studied for more than one
24 hundred (100) years, a robust, calibrated sensor capable of measuring fluctuating shear
25 stress is still elusive. Even with new materials and manufacturing processes that have
26 become available over the past fifteen (15) years that enable the fabrication of miniature
27 sensors, the expected improvements have been offset by some of the same problems

larger sensors experienced as well as some new difficulties associated with the small sensors.

Table 1 - Shortcomings of some conventional sensors

Direct-Force Balances	Thermal Sensors	Velocity Profile Measurement
<ul style="list-style-type: none"> • Small shear force • Pressure gradients • Required gaps • Sensitivity to vibration • Sensitivity to thermal expansion 	<ul style="list-style-type: none"> • Temperature drift • Conduction to substrate • Non-unique calibrations <ul style="list-style-type: none"> ◦ Reynolds analogy • Sensitivity to unknown fluid composition and dust 	<ul style="list-style-type: none"> • Time-intensive • Mean measurement only • Seeding sometimes required • Flow field access required • Semi-empirical fits susceptible to error

Existing wall shear stress sensors can be split into two categories: conventional approaches and small-scale sensors that take advantage of the materials and manufacturing processes now available. Some sensors that have been investigated for years at large scales are being reduced in size to investigate benefits arising from scaling. Direct force balances, thermal sensors, and sensors measuring points in the velocity profile have all been investigated recently at small-scale. At the large scale, these sensors suffer from several shortcomings (see Table 1). As a result, measurement techniques such as oil-film interferometry are gaining widespread use for mean wall shear stress measurements. Due to the nature of the oil-film technique, it is likely that its use will be limited outside the laboratory environment, and it is not a candidate for fluctuating measurements.

The characteristics of an ideal wall shear stress sensor include:

- High sensitivity
- High Spatial Resolution
- High Bandwidth
- Easily Integrated
- Statically and dynamically calibrated
- Robust

- 1 • Low power consumption
- 2 • Environmentally stable

3

4 Benefits of creating sensors at the small scale are possible because of the advances
5 in microelectrical-mechanical system (MEMS) and micromachining technologies now
6 available. The approach to date has primarily been to reduce the size of conventional
7 sensors, and it has met with mixed success. Four approaches (velocity-based sensors,
8 force-balance techniques, thermal, and surface acoustic wave sensors) have been
9 attempted and are described below. For further details, consult the recent review by
10 Naughton and Sheplak (2003).

11 Over the past several years, miniature velocity measurement sensors (MOEMS -
12 Micro-Optical-Electro-Mechanical Systems) have been introduced. These sensors make
13 streamwise velocity measurements at two or more points in the flow, and, using boundary
14 layer similarity laws, the wall shear stress is inferred. One method uses the diverging
15 fringe method. Measurements are made in a diverging fringe pattern created by two laser
16 beams interfering in the near-wall region (laminar sublayer) of the boundary layer. In this
17 region, velocity increases linearly with distance from the wall, and thus the velocity
18 gradient is constant. Particles passing through these fringes produce a scattered light
19 signal whose frequency is proportional to the velocity gradient. Although particles
20 passing through the different heights have different speeds, they will produce nearly
21 identical signals. Having obtained the velocity gradient, the wall shear stress may be
22 easily calculated. Recent work extends this technique to higher Reynolds number by not
23 limiting the measurement region to the laminar sublayer. Velocities are measured at two
24 points in the boundary layer and Spalding's equation is used to fit the points and to
25 determine the wall shear stress. For both of these methods, MOEMS enables small probe
26 volumes and a compact sensor. The method will measure fluctuations, but the
27 relationship of these fluctuations to variations in wall shear stress needs to be established,
28 particularly for the two-point measurement system.

29 Although these methods show some promise, there are some drawbacks as well.
30 The method requires seeding, and the need for a laser in the system limits how small the

1 sensor can be made. These sensors will be invaluable in the laboratory for evaluating
2 new concepts such as that suggested in the current proposal, but this sensor is unlikely to
3 attain widespread use outside the laboratory environment.

4 Small-scale implementations of direct force balance methods are known. In these
5 designs, elastic legs (tethers) support a floating element. As shear stress is applied to the
6 sensor surface, the sensor deflects laterally. Capacitive, piezo-resistive, and optical
7 methods have been used to determine the position of the sensor. In another method, a
8 sensor has been developed that incorporates an electro-static comb-finger design that
9 could be used for capacitive sensing of floating element position or could be used to
10 actuate the sensor. A drawback of floating element designs is their limitations in dirty
11 environments due to the necessary gaps between the floating element and the surrounding
12 surface. Some sensors require a remote light source that makes the sensor sensitive to
13 vibration.

14 In the past, small-scale silicon thermal sensors offered great promise due to their
15 improved resistance to conduction compared to traditional, larger-scale implementations.
16 With small-scale silicon thermal sensors, a small element is heated to a temperature
17 above that of the flow. Changes in convective heat transfer from the sensor result in
18 changes in the resistance of the heating element. The resistance is thus a measure of the
19 heat transfer and is assumed to be proportional to the wall shear stress through Reynolds
20 analogy. Only one small-scale thermal sensor has been robustly calibrated and those
21 results were not encouraging. Thus, in order to make quantitative measurements with
22 such sensors, a more complete understanding of coupled fluid dynamic/heat transfer
23 processes, unsteady conduction to the substrate, temperature drift, and sensitivity to fluid
24 transport properties is required.

25 The surface acoustic wave (SAW) sensor uses an oscillator that generates acoustic
26 waves that propagate along a surface where they are sensed by an input transducer.
27 Frequency shift in the wave is correlated to pressure and shear forces acting on the
28 surface.

29 It is clear from the results to date that small-scale wall shear stress sensor
30 development is still a work in progress. Much work has been done on these sensors, but

1 unfortunately, few of the studies have reported rigorous characterization and calibration.
2 Although these methods do show some promise, they are simply extensions of
3 conventional techniques and thus inherit some of the same problems.

4 Accordingly, there exists a need for a dynamic resonant wall shear stress sensor
5 capable of making measurements in fluids and having a high bandwidth. Additionally, a
6 need exists for a dynamic resonant wall shear stress sensor having high spatial resolution.
7 Furthermore, there exists a need for a dynamic resonant wall shear stress sensor having
8 high sensitivity capable of fluctuating wall shear stress measurements in all kinds of
9 flows on all kinds of surfaces.

10

11 SUMMARY

12 The present invention is a wall shear stress sensor for measuring the shear stress
13 due to fluid flow over a test surface. The wall shear stress sensor is comprised of a wall
14 shear stress sensor body and an active sensing surface. An elastic mechanism mounted
15 between the shear stress sensor body and the active sensing surface allows movement
16 between the shear stress body and the active sensing surface. A driving mechanism
17 forces the active sensing surface to oscillate. A transducer measures displacement of the
18 active sensing surface relative to the shear stress sensor body. Changes in the nature of
19 the fluid properties or flow over the sensor measurably changes the motion of the active
20 sensing surface, or changes the force and power required from a control system in order
21 to maintain constant motion.

22 In addition, the present invention includes a sensor for measuring wall shear
23 stress. The wall shear stress sensor comprises an oscillating plate and at least one wire
24 attached to the sensor body that suspends the oscillating plate. A drive coil is mounted to
25 the sensor body. A transducer is mounted to the sensor body wherein, as the plate
26 oscillates, the transducer measures the displacement of the oscillating surface. A time
27 varying shear force imposes drag with the magnitude of the shear drag force being
28 different at different points within a single cycle such that the variation of shear forces
29 within a cycle results in a dampening of the resonant forced vibration of the active

1 sensing plate and a consequent change in oscillation amplitude and phase offset. Note:
2 This is an actual implementation - is this important?

3 The present invention further includes a method for measuring wall shear stress.
4 The method comprises providing an active sensing surface, elastically mounting the
5 active sensing surface to the sensor body, forcing the active sensing surface to oscillate,
6 and measuring displacement of the active sensing surface.

7 Furthermore, the present invention includes a method for measuring wall shear
8 stress. The method comprising, oscillating a plate, imposing drag with time varying shear
9 forces, dampening of resonant forced vibration of the oscillating plate with a change in
10 oscillation magnitude and phase offset, and measuring the amplitude and/or phase offset,
11 or measuring the change in the force and power required from a control system in order to
12 maintain constant motion.

13 14 BRIEF DESCRIPTION OF THE DRAWINGS

15 FIG. 1 is a schematic view illustrating an oscillating shear stress sensor,
16 constructed in accordance with the present invention, with a time history of the
17 fluctuating shear force on the sensor;

18 FIG. 2a is a top view illustrating another embodiment of a dynamic resonant shear
19 stress sensor, constructed in accordance with the present invention; and

20 FIG. 2b is a side view illustrating of the shear stress sensor of FIG. 2a, constructed
21 in accordance with the present invention;

22 FIG. 3a contains amplitude and phase data from an open-loop, periodic, resonant
23 implementation of an oscillating shear stress sensor constructed in accordance with the
24 present invention;

25 FIG. 3b contains amplitude data from a closed-loop, periodic, resonant
26 implementation of an oscillating shear stress sensor constructed in accordance with the
27 present invention;

28 FIG. 4a compares normalized peak rms values, extracted from plots of the form of
29 FIG. 3a, between open loop data sets obtained in the 0.793 and 3.18 mm high channel test
30 sections. In all of the data presented in this paper the sensor plate was run with

1 displacement amplitudes (half of peak-to-peak value) of approximately 264, 467 and 668
2 microns. The normalization procedure was to divide each peak rms measurement by the
3 zero shear stress intercept obtained by linear regression of the initial few data points.

4 Both data sets show an initial linear response at each drive level. Both data sets show
5 that the highest sensitivity corresponded to the lowest drive value.

6 FIG. 4b shows that the 3.18 mm high channel data shows a clear decrease in sensitivity
7 with increasing shear stress level. The sensitivity of the highest drive level within the
8 .793 mm high channel data set is nearly the same as that of the highest drive level within
9 the 3.18 mm high channel data set, while the sensitivity of the lowest drive level within
10 the .793 mm high channel data set is clearly greater than that of the lowest drive level
11 within the 3.18 mm high channel data set;

12 FIGS. 5a and 5b compare normalized minimum rms values, extracted from plots
13 of the form of FIG. 3b, between closed loop data sets obtained in the 0.793 and 3.18 mm
14 high channel test sections. Where again the sensor plate was run with displacement
15 amplitudes (half of peak-to-peak value) of 264, 467 and 668 microns. The comparative
16 response is quite similar to that measured during the open loop experiments. Again both
17 data sets show an initial linear response at each drive level, with a subsequent decrease in
18 sensitivity evident at higher shear stresses in the 3.18 mm channel height data. Again
19 both the .793 and 3.18 mm high channel data sets show that the highest sensitivity
20 corresponded to the lowest drive level. The sensitivity of the medium and highest drive
21 level within the .793 mm high channel data set is nearly the same as that of the medium
22 and highest drive level within the 3.18 mm high channel data set, while the sensitivity of
23 the lowest drive level within the .793 mm high channel data set is clearly greater than that
24 of the lowest drive level within the 3.18 mm high channel data set;

25 FIG. 6 is a perspective view illustrating a preferred embodiment of the present
26 invention; and

27 FIGS. 7 and 8 are perspective views illustrating the preferred embodiment of the
28 present invention as positioned within a wind tunnel.

29
30 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

1 As illustrated in FIG. 1, the present invention is a dynamic resonant wall shear
2 stress sensor, indicated generally at 10, for sensing changes in wall shear stress when
3 operating near resonance.

4 Description of Sensor shown in Fig. 1

5 The wall shear stress sensor 10 of the present invention includes an active sensing
6 surface 12 attached to the sensor body 14. Preferably, the active sensing surface 12 is
7 connected to the sensor body 14 via elastic elements (commonly called tethers) 20 such as
8 springs or the like mounted between the active sensing surface 12 and the sensor body 14.
9 In the preferred embodiment, the wall shear stress sensor 10 includes four elastic legs 20
10 that mount the active sensing surface 12 to the sensor body 14.

11 In addition, the wall shear stress sensor 10 includes a driving mechanism, 22, and
12 a transducer, 24. The driver 22 forces the active sensing surface 12 to oscillate. The
13 transducer 24 measures the local displacement, and/or velocity, and/or acceleration of the
14 active sensing surface 12 relative to the sensor body 14.

15 The fluctuating shear stress acting on the active sensing surface 12 depends on the
16 frequency and amplitude of the shear stress sensor movement and is not in phase with the
17 displacement or the velocity. Thus, the shear stress sensor 10 can be thought of as a
18 weakly non-linear damped (both positive or negative) forced vibration mechanism. As a
19 result, the active sensing surface's 12 oscillatory movement will change as the wall shear
20 stress changes.

21 Capabilities Of Device Described

22 The wall shear stress sensor 10 of the present invention is a wall shear stress
23 sensor based on a new oscillatory motion sensing technique. Using the sensing
24 technique, a lightweight, low-cost wall shear stress sensor 10 capable of fluctuating wall
25 shear stress measurements has been developed. Two such wall shear stress sensors 10
26 mounted at an angle to each other provide shear stress magnitude and direction. Arrays
27 of the wall shear stress sensors 10 provide spatial and temporal information about the
28 wall shear stress field. Such wall shear stress sensors 10 are beneficial for many flow
29 control applications. For instance, a control scheme for reducing skin-friction drag has
30 been developed that uses wall shear stress as the sensed input to the control system.

1 Other potential uses of the fluctuating wall shear stress sensors 10 of the present
2 invention exist in the biomedical and industrial areas where diagnostic sensing, process
3 and system health monitoring, and process control are important.

4 A number of different basic operating modes are possible with any single specific
5 oscillating motion sensing device. Specific devices may use translation or rotary
6 oscillatory motion or the motion that result from the distortion of the body. These include
7 fixed input or open loop control modes, variable input or closed loop control modes, and
8 operation under periodic or non-periodic motion. Each of these are discussed below.

9 Periodic Motion Operation

10 The wall stress sensor 10 of the present invention when operated in open-loop or
11 closed-loop periodic modes utilizes the extremely high sensitivity of a high Q dynamic
12 resonant-motion system to measure the wall shear stress. By definition a high Q resonant
13 system has little damping and as a consequence high resonant vibration amplitudes occur
14 over a narrow range of frequencies. The high Q characteristics of our device results in
15 large amplitude periodic motion under very low periodic input forcing. The addition of
16 small periodic force disturbances such as that due to the surface shear forces that are out
17 of phase with that of the drive forcing strongly reduces the motion amplitude unless
18 compensated for by a control system. *Because of these active motion characteristics our*
19 *design is categorically different than existing wall shear stress sensors that measure a*
20 *shear stress by a time constant (static) displacement of a sensing surface. The extreme*
21 *sensitivity of resonant systems to force disturbances increases the shear stress sensitivity*
22 *of our sensor hundreds or even thousands of times over that of a comparable static*
23 *displacement sensor.*

24 Open-Loop, Periodic Motion Operation

25 Periodic motion dynamic systems operating at or near resonance are very sensitive
26 to small changes in forces. The wall shear stress sensor 10 of the present invention is
27 specifically designed such that wall shear stress on the surface of the active sensing
28 surface 12 acts to damp the resonant system. By measuring changes in the resonance
29 (amplitude and/or phase of sensor motion) due to a change in damping, the wall shear
30 stress can be determined. Part of the benefit of the dynamic shear stress sensor 10 over

1 static force balance sensors is that other forces (such as pressure differences across the
2 sensor due to pressure gradients) affect the static motion but do not affect the dynamic
3 motion and thus do not affect the sensitivity to wall shear stress. The sensor can also be
4 driven by the driving mechanism 22 at frequencies well above or below resonance,
5 although this would appear to be less desirable, resulting in a different response to the
6 fluctuating shear stress on the active sensing surface 12.

7 Data from an implementation of an open loop, periodic, resonant sensor is shown
8 in Fig. 3. In this experiment, the driving frequency was varied while the wall shear stress
9 was varied. Repeating this measurement for several shear stress levels yielded the curves
10 in Fig. 3. These data represent the first such measurements of a open-loop, periodic,
11 resonant wall shear stress sensor and were acquired at the University of Wyoming using a
12 prototype device. As is evident from the figure, an increase in wall shear stress tends to
13 decrease the amplitude of the motion of the active sensing surface. A small frequency
14 shift that is also observed.

15 Closed Loop, Periodic Motion Operation

16 Another mode in which the wall shear stress sensor 10 could be operated would
17 use closed-loop feedback to control the motion of the active sensing surface 12. In this
18 configuration, the force input from the driving mechanism 22 to the active sensing
19 surface member 12 is controlled so as to result in approximate or exact specified periodic
20 motion. As the wall shear stress changes, the magnitude and/or phase characteristics of
21 the forcing will change. Therefore, any measure of the controlled time dependant or
22 average force output from the driving mechanism 22 is a measure of the surface shear
23 stress.

24 Data from an implementation of a closed-loop, periodic, resonant sensor is shown
25 in Fig. 4. In this experiment, the driving frequency was varied while the wall shear stress
26 was varied. Repeating this measurement for several shear stress levels yielded the curves
27 in Fig. 4. This data represents the first such measurements of an closed loop feedback
28 controlled, periodic, resonant wall shear stress sensor which was acquired at the
29 University of Wyoming using a prototype device. As is evident from the data in the
30 figure, an increase in wall shear stress tends to increase the voltage required from the

1 driving mechanism 22 to drive the active sensing surface 12. Furthermore, an increase in
2 the wall shear stress results in a measurably larger phase offset between the driving force
3 and the control input. Both sensitivities are greatest around the minimum drive
4 amplitude, which should correspond to the resonant frequency.

5 6 Open-Loop, Non-Periodic Oscillatory Motion Operation

7 In some situations, it may be preferable to use the wall shear stress sensor 10 in alternate
8 modes. The wall shear stress sensor 10 could also be driven by the driving mechanism 22
9 in a non-periodic fashion (for example a pulse input) and measurable changes in the
10 transient motion of the sensor can be used to determine the wall shear stress. For instance
11 under a pulse input from a static initial condition a measurably greater motion attenuation
12 would occur in a direction into the flow as compared to the motion in a direction away
13 from the flow. This mode of operation may become increasingly important as the size of
14 the device becomes smaller, or as the strength of the fluid damping becomes greater.

15 16 Closed Loop, Non-periodic Oscillatory Motion Operation

17 Another mode in which the wall shear stress sensor 10 could be operated would
18 use closed-loop feedback to control the non-periodic motion of the active sensing surface
19 12. In this configuration, the force input from the driving mechanism 22 to the active
20 sensing surface member is controlled so as to result in approximate or exact specified
21 non-periodic motion. As the wall shear stress changes, the magnitude and/or phase
22 characteristics of the forcing will change. Therefore, any measure of the controlled time
23 dependant output from the driving mechanism 22 is a measure of the surface shear .

24 Similarly to the immediately preceding open loop discussion, this mode of operation may
25 become increasingly important as the size of the device becomes smaller, or as the
26 strength of the fluid damping becomes greater.

27 28 Applicability to Many Flows and Calibration

1 The wall shear stress sensor 10 of the present invention is a lightweight,
2 inexpensive, scaleable wall shear stress sensor capable of high-bandwidth fluctuating
3 shear stress measurements on many different surfaces in many different flows. The
4 different types of flows include: (1) subsonic, transonic, supersonic, and hypersonic
5 flows, (2) laminar and turbulent flows, (3) incompressible and compressible flows, and
6 (4) linear or non-linear rheology fluids. To achieve this goal, the wall shear stress sensor
7 10 is calibrated both statically and dynamically by in situ dynamic calibration and/or
8 other means.

9 The benefits of the wall shear stress system's 10 dynamic-resonant design are that,
10 unlike many sensors, the wall shear stress sensor 10 is directly sensitive to wall shear
11 stress (it is a direct sensing method) and thus can provide measurements in flows with
12 varying temperature, varying composition, contamination, etc. It can also be used in
13 separated flows. Thus, the wall shear stress sensor 10 can be applied in an extremely
14 wide range of applications.

15 Since fluctuating wall shear stress is very sensitive to the state of the boundary
16 layer, its measurement is key to providing the sensing necessary to control wall-bounded
17 flows. Wall shear stress is very sensitive to, and therefore a good indicator of, the flow
18 conditions above the surface. Therefore, miniature wall shear stress sensors 10 are
19 effective tools useful for diagnostic purposes, flow monitoring, and flow control. The
20 novel wall shear stress sensor 10 described in the present application is specifically
21 designed to take advantage of the small sensor sizes possible with today's manufacturing
22 methods.

23 24 Description of Specific Device

25 In an embodiment of the present invention, as illustrated in FIGS. 2a and 2b, the
26 shear stress sensor 10 is simple and robust - it contains only four (4) major elements. The
27 first element is a very thin, lightweight oscillating active sensing surface 12. Very fine,
28 high tensile strength wires 20 suspend the oscillating plate 12. The longitudinal motion
29 of the oscillating plate 12 is driven at or near the resonant frequency by a fixed frequency,
30 electromagnetic drive coil 22. A linear Hall effect transducer 24 continuously measures

1 the position of the device. As the surface plate 12 oscillates, a time varying wall shear
2 stress imposes a time varying shear force. The magnitude of this shear force is different
3 at different points within a single cycle. The variation of shear forces within a cycle
4 results in a dampening of the resonant forced vibration of the oscillating plate and a
5 consequent change in oscillation amplitude and phase offset, or results in a change in the
6 time varying force and instantaneous or average power required from a control system in
7 order to maintain approximate or exact specified motion. Depending on the
8 implementation, either the change in oscillation amplitude or phase offset, or the change
9 in required force and power is large and easily measured by standard analog or digital
10 electronics.

11 Preferably, as illustrated in FIGS. 5 – 7, the oscillating plate 12 is located just
12 ahead of an inset plate that contains a small electric solenoid which provides electro-
13 magnetic forcing. Position transduction is accomplished via a calibrated magnetic Hall
14 probe sensor or by a line laser beam and a photodiode. During operation of the present
15 prototype, the oscillating plate 12 vibrates at approximately two hundred and sixty (260
16 Hz) Hertz with a longitudinal displacement amplitude of approximately one hundred (100
17 micrometers) micrometers. In this embodiment of the present invention, the shear stress
18 sensor 10 requires a vertical inset to accommodate the drive motor parts. The wall shear
19 stress sensor 10 is mated to the primary flow surface plate with precision, as the flow
20 must not separate in front of the oscillating plate 12.

21 Scaling

22 An important extension of the present invention is to take advantage of scale to
23 make the dynamic-resonant sensor effective for measuring fluctuating wall shear stress.
24 As the size of the wall shear stress sensor 10 decreases, the frequencies at which it will
25 resonate increase thereby increasing sensor bandwidth. Additionally, this smaller scale,
26 higher frequency wall shear stress sensors 10 will have a reduced sensitivity to lower
27 frequency external noise and vibration. In other cases, the scale of the flow may dictate
28 the use of a larger size sensor. As a result, the active sensing surface 12 of the wall shear
29 stress sensor 10 could vary in size by several (10 -12) orders of magnitude depending on

1 the application whose requirements might range from small size and high frequency
2 response to large size and low frequency response.

4 Methods of Fabrication

5 The large range of appropriate sizes of these sensors necessitates the use of many
6 different specific fabrication methods and materials. These may include but are not
7 limited to, (1) mm or larger scale devices fabricated from metals, ceramics, glass, or
8 plastics, and (2) silicon based, micron scale micro-electro-mechanical devices, and (3)
9 nanometer scale nano-electro-mechanical devices including those that are utilize carbon
10 or inorganic nano-wires or nano-tubes.

12 Methods of Forcing

13 The large range of appropriate sizes of these sensors necessitates the use of many
14 different specific forcing means. These may include but are not limited to, any
15 mechanical, electrical, magnetic or optical methods. Mechanical methods include but are
16 not limited to forces transmitted through solid members or machine elements such as
17 springs, or forces transmitted through fluid media such as hydraulic or acoustic forces.
18 The forcing may result from a change in drag characteristics by changing the active
19 sensing element's surface properties or geometry. The forcing waveform may be periodic
20 or non-periodic, and it may be analog or digitally based including but not limited to as
21 pulse width modulation. The forcing mechanism may be propulsion including but not
22 limited to that from a fluid jet, or inertial forces such as from an imbalanced rotor or an
23 oscillating mass.

25 Methods of Motion Transduction

26 The large range of appropriate sizes of these sensors necessitates the use of many
27 different specific motion transduction means. These may include but are not limited to,
28 mechanical, electrical, magnetic, radiative, or any form of optical transduction including
29 but not limited to those based on encoders, polarizers, moire patterns, interferometry,

1 graded density filters, liquid crystals, apertures, reflective surfaces or imaging. The
2 motion transduction means may be in analog, digital, continuous or discontinuous form.

3 Methods of Force Transduction

4 In a closed-loop feedback system a measure of the time-dependant forcing
5 becomes a measure of the shear stress. Therefore some means for determining the
6 instantaneous or average forcing is required. This may be accomplished by directly
7 measuring the force on the active sensor surface member by a transducer including but
8 not limited to a load cell, or by indirectly measuring the force on the active sensor surface
9 member by measuring the input into the forcing means. This may include but is not
10 limited to measuring the voltage or current supplied to an electro-magnetic coil.

12 Novelty of Design, Impact, Applications

13 The wall shear stress sensor 10 employs a novel sensing approach and is not just
14 an incremental improvement to an existing method. The wall shear stress sensor 10 of
15 the present invention when operated in open-loop or closed-loop periodic modes is the
16 first sensor to utilize the extremely high sensitivity of a high Q dynamic resonant-motion
17 system to measure wall shear stress.

18 The wall shear stress sensor 10 has several desired characteristics: (1) small size,
19 (2) enhanced sensitivity, (3) good temporal resolution, (4) insensitivity to pressure
20 gradient, (5) may be assembled into compact, multi-directional arrays, and (6) may be
21 combined with actuators in a closed-loop control system.

22 The wall shear stress sensor 10 of the present invention has many advantages.
23 Any process where pressure and mass flow are measured would be a candidate for a wall
24 shear stress sensor 10. This represents an enormous number of applications. Since it is
25 possible to manufacture the wall shear stress sensors 10 as single sensors, in large arrays,
26 and in sensor/actuator systems, the wall shear stress sensors 10 can be applied to new
27 areas where no equivalent technology exists today. One application for small-scale wall
28 shear stress sensors 10 is the aerospace industry where vehicle health monitoring and
29 flow-control applications could benefit from this sensor. A specific application would be
30 a sensing system for stall that would be much more sensitive than today's methods. This

1 would be particularly important for high-altitude subsonic aircraft that operate near stall.
2 The medical field also has interest in wall shear stress measurements in arteries where
3 low mean levels of and/or high fluctuations of wall shear stress are associated with
4 plaques that form as part of arteriosclerosis. The industrial field could benefit from such
5 a sensor in process monitoring and control applications. Another application would be
6 sensing wall shear stress in coordination with sensors for detecting chemical and
7 biological agents. The shear stress sensors 10 would monitor and/or control the air
8 passing by the biological/ chemical sensor by sensing the state of the flow.

9 An application with significant potential that could benefit from accurate
10 fluctuating wall shear stress sensing would be catalyst beds. In this application, wall
11 shear stress sensors 10 would monitor the wall shear flow just ahead of or just exiting a
12 flow-through catalyst bed. This will allow for the continuous optimization of the target
13 chemical process in situations where the flow properties are changing due to the
14 degradation of the catalyst media. The wall shear stress sensors 10 may be arranged on
15 the walls or on baffles so that a large matrix of local flow conditions may be continuously
16 measured, which allows for the identification of local flow blockage. The present
17 industrial method of using turbine flow meters or orifice pressure sensors is insensitive to
18 local flow variations, exacts pressure losses, and is prone to breakdown from mechanical
19 failure or chemical attack.

20 Potentially the largest beneficiary of the wall shear stress sensor 10 is industry.
21 Since the wall shear stress sensor 10 directly measures shear stress, it can be adapted to
22 work in challenging environments such as dusty flows and flows with mixed
23 composition. In industrial flows, there is also a need to characterize and monitor flows,
24 such as concentrated suspensions, in manufacturing processes. An example of how the
25 wall shear stress sensor 10 might be used in this type of application is to monitor a flow's
26 viscosity if the velocity profile is known (i.e. laminar pipe flow and the mass flow is
27 known).

28
29 Summary

1 In sum, the development of new concepts for sensing wall shear stress is long
2 overdue. The wall shear stress sensor 10 of the present invention measures small shear
3 forces using a driven dynamic sensor. By having the wall shear stress sensor 10 oscillate
4 in a plane tangential to the wall shear stress, the wall shear stress sensor 10 is very
5 sensitive to changes in wall shear stress since this additional force acts as a complex time-
6 dependent force on the sensor. Response of the resonant system can be measured and is
7 linked to the wall shear stress. Also, the wall shear stress sensor 10 is largely insensitive
8 to the pressure gradient, a large source of error for some previous approaches. The wall
9 shear stress sensor 10 of the present invention is a wall shear stress sensor with high
10 bandwidth, high spatial resolution, and high sensitivity capable of fluctuating wall shear
11 stress measurements in all kinds of flows on all kinds of surfaces.
12

13 The foregoing exemplary descriptions and the illustrative preferred embodiments
14 of the present invention have been explained in the drawings and described in detail, with
15 varying modifications and alternative embodiments being taught. While the invention
16 has been so shown, described and illustrated, it should be understood by those skilled in
17 the art that equivalent changes in form and detail may be made therein without departing
18 from the true spirit and scope of the invention, and that the scope of the present invention
19 is to be limited only to the claims except as precluded by the prior art. Moreover, the
20 invention as disclosed herein, may be suitably practiced in the absence of the specific
21 elements that are disclosed herein.
22

ABSTRACT

A shear stress sensor for measuring fluid wall shear stress on a test surface is provided. The wall shear stress sensor is comprised of an active sensing surface and a sensor body. An elastic mechanism mounted between the active sensing surface and the sensor body allows movement between the active sensing surface and the sensor body. A driving mechanism forces the shear stress sensor to oscillate. A measuring mechanism measures displacement of the active sensing surface relative to the sensor body. The sensor may be operated under periodic excitation where changes in the nature of the fluid properties or the fluid flow over the sensor measurably changes the amplitude or phase of the resonant or near resonant motion of the active sensing surface, or changes the force and power required from a control system in order to maintain specified resonant or near resonant periodic motion. The device may be also be operated under non-periodic excitation where changes in the nature of the fluid properties or the fluid flow over the sensor change the transient motion of the active sensor surface or change the force and power required from a control system to maintain a specified transient motion of the active sensor surface.

Fig. 1

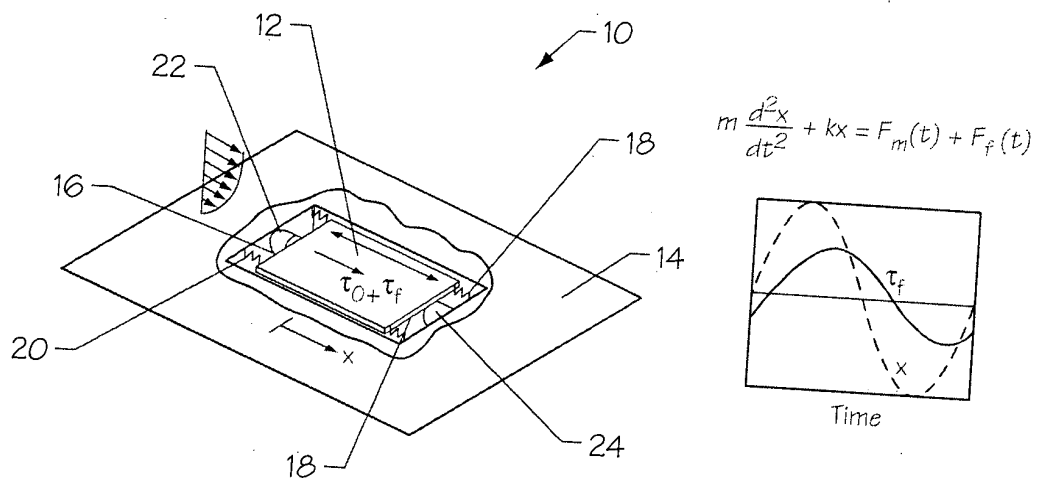


Fig. 2a

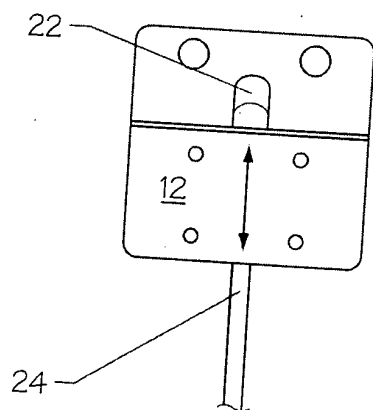
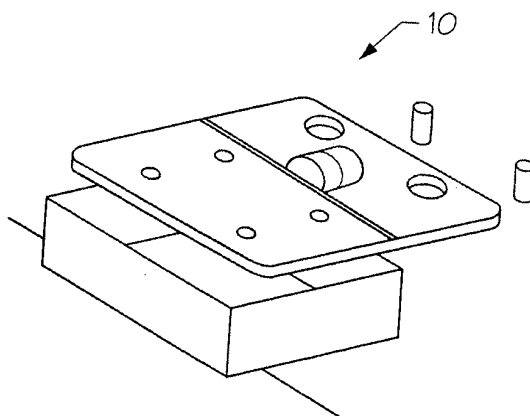


Fig. 2b



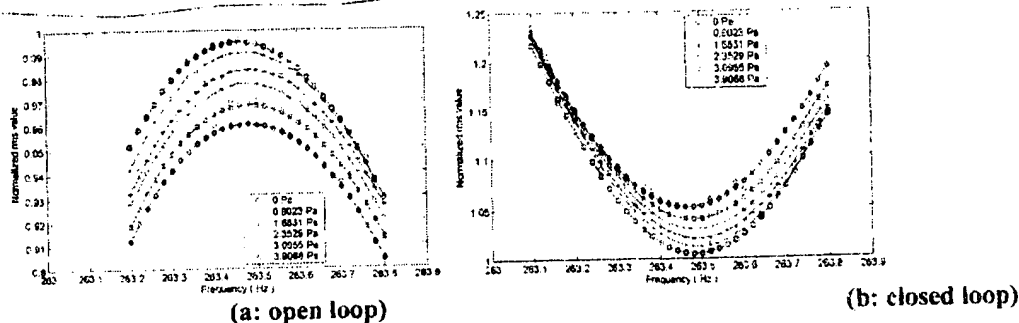


Fig. 3 (a) Open loop experiment, rms value of the position transducer output versus drive frequency curves. (b) Closed loop experiment, rms value of the motor drive current versus frequency curves.

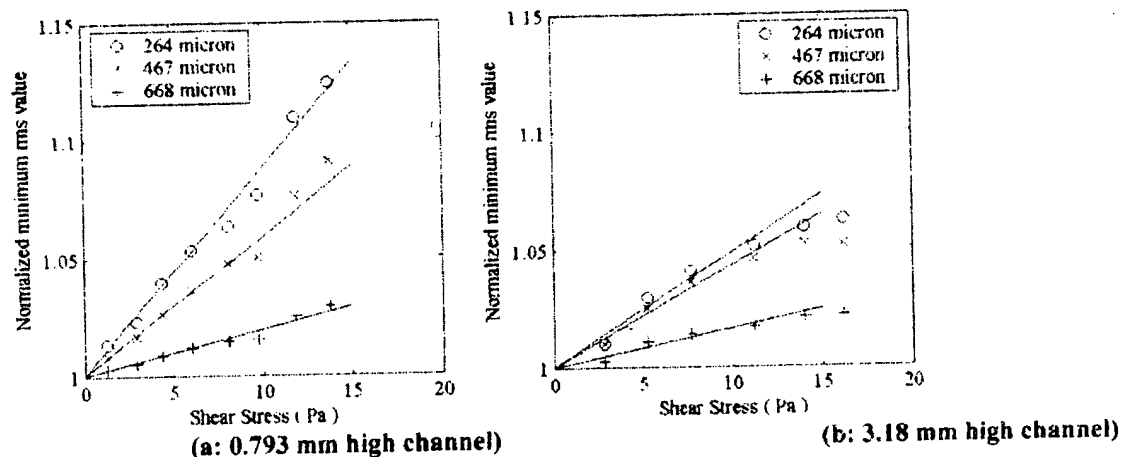


Fig. 5 Closed loop normalized peak rms values. (a) 0.793 mm high channel results. (b) 3.18 mm high channel results.

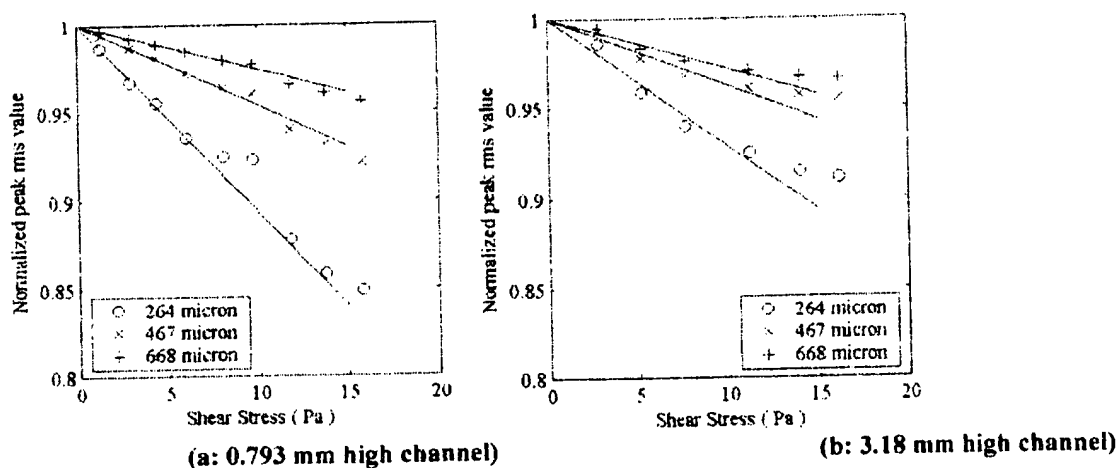


Fig. 7 Normalized peak rms values obtained under open loop operation. (a) 0.793 mm high channel results. (b) 3.18 mm high channel results.

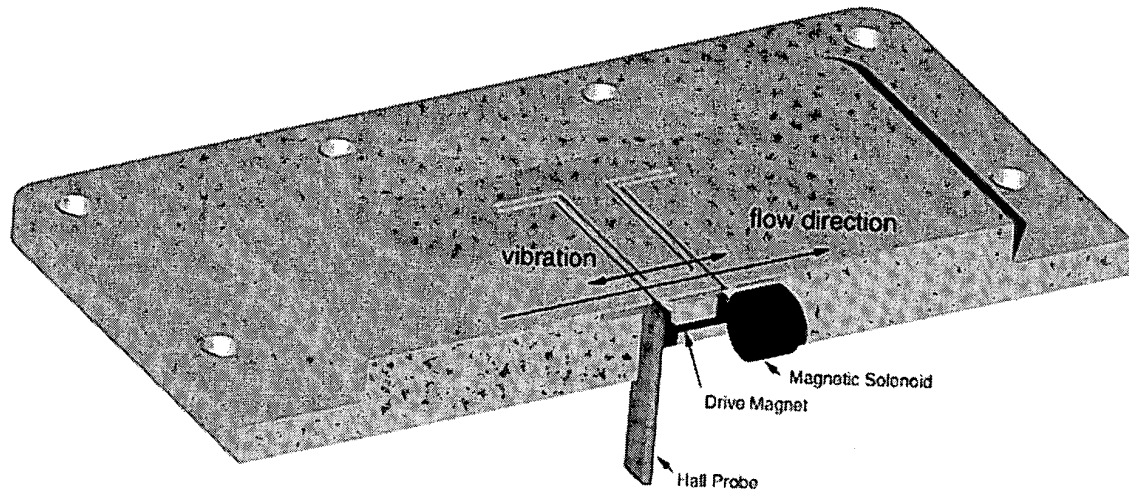


FIG. 6

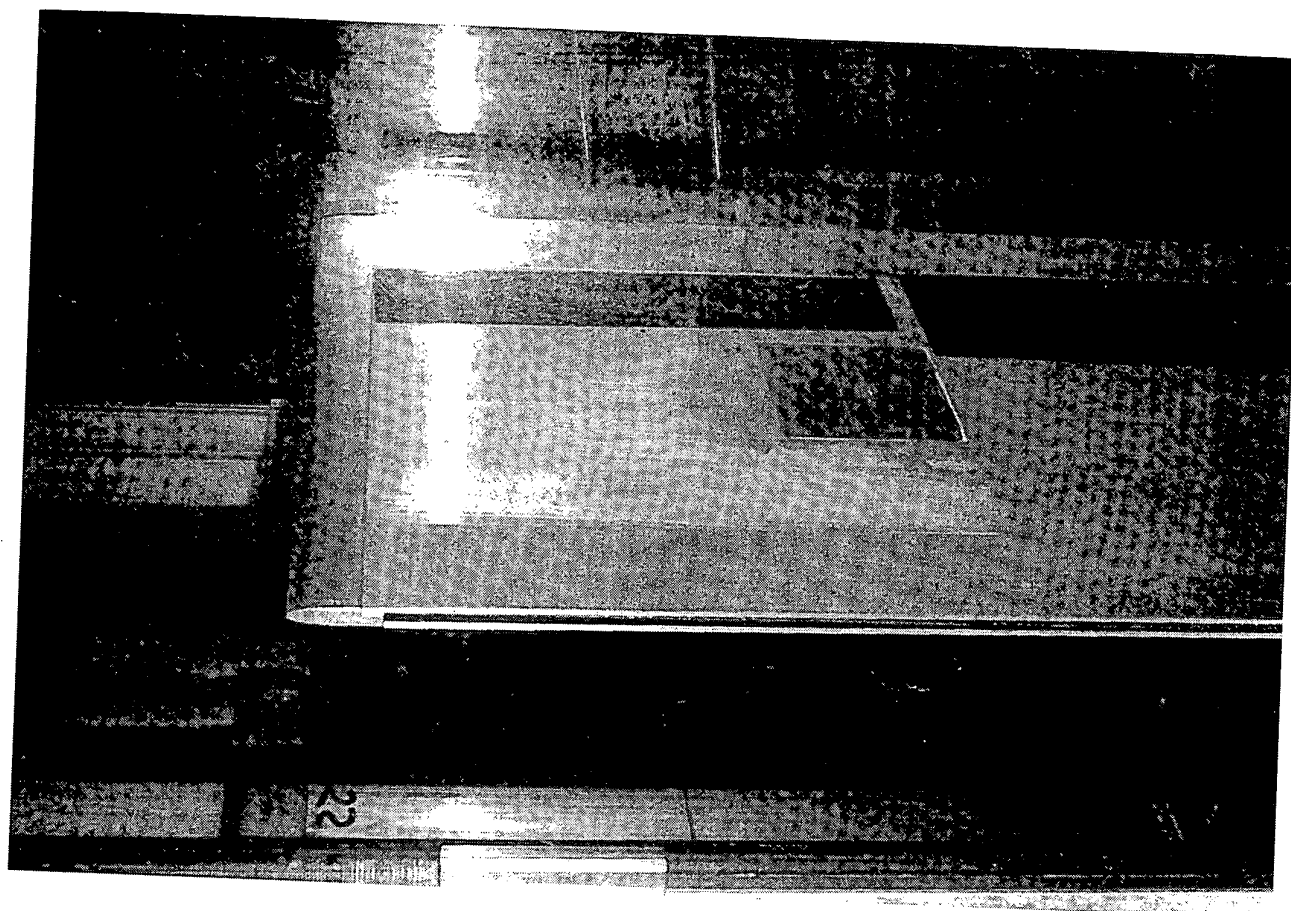


FIG. 7

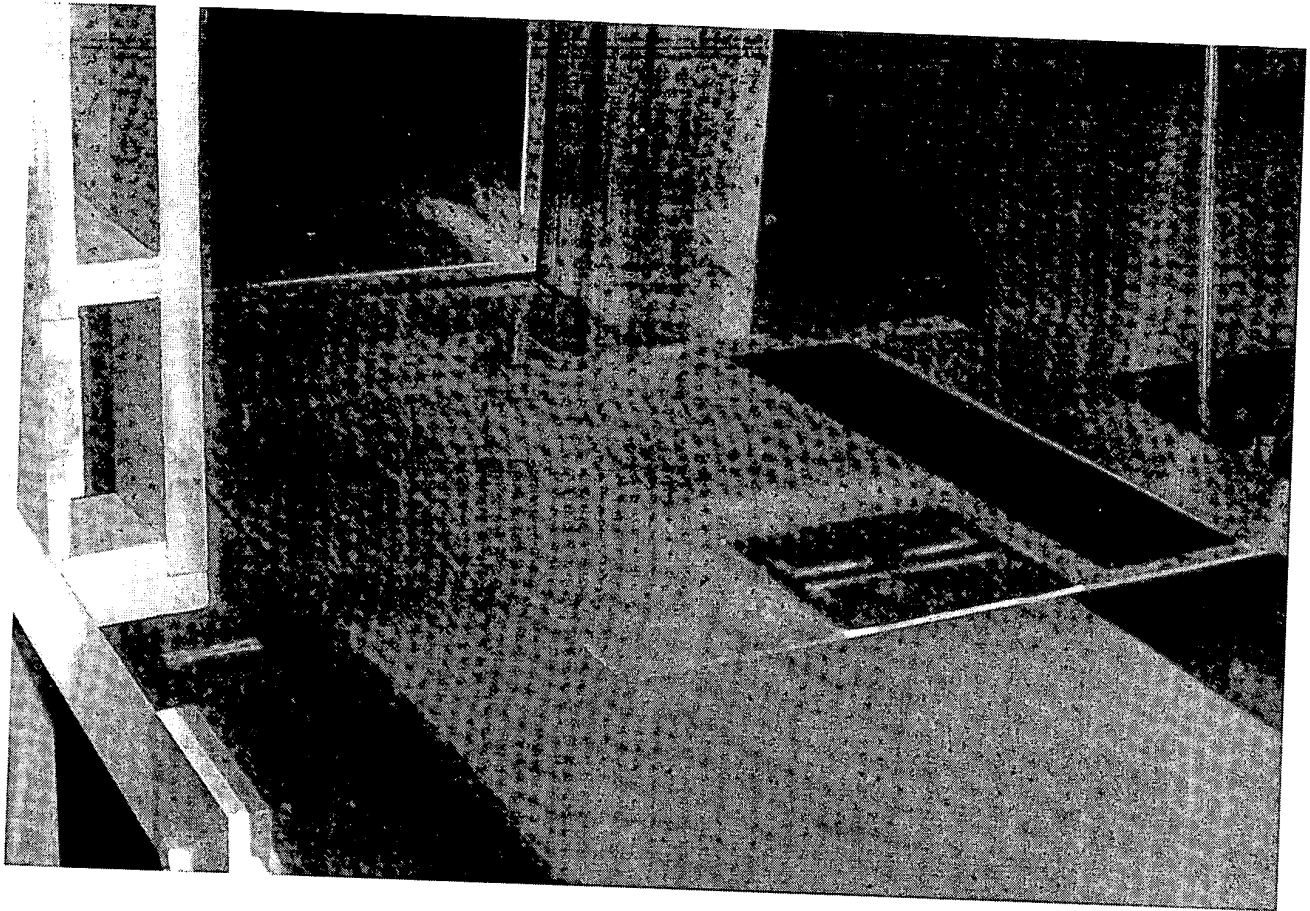


FIG. 8